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Automatic detection of selective arterial devices for advanced visualization during abdominal aortic aneurysm endovascular repair

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A B S T R A C T

Here we address the automatic segmentation of endovascular devices used in the endovascular repair (EVAR) of abdominal aortic aneurysms (AAA) that deform vascular tissues. Using this approach, the vascular structure is automatically reshaped solving the issue of misregistration observed on 2D/3D image fusion for EVAR guidance. The endovascular devices we considered are the graduated pigtail catheter (PC) used for contrast injection and the stent-graft delivery device (DD). The segmentation of the DD was enhanced using an asymmetric Frangi filter. The segmented geometries were then analysed using their specific features to remove artefacts. The radiopaque markers of the PC were enhanced using a fusion of Hessian and newly introduced gradient norm shift filters. Extensive experiments were performed using a database of images taken during 28 AAA-EVAR interventions. This dataset was divided into two parts: the first half was used to optimize parameters and the second to compile performances using optimal values obtained. The radiopaque markers of the PC were detected with a sensitivity of 88.3% and a positive predictive value (PPV) of 96%. The PC can therefore be positioned with a majority of its markers localized while the artefacts were all located inside the vessel lumen. The major parts of the DD, the dilatator tip and the pusher surfaces, were detected accurately with a sensitivity of 85.9% and a PPV of 88.7%. The less visible part of the DD, the stent enclosed within the sheath, was segmented with a sensitivity of 63.4% because the radiopacity of this region is low and uneven. The centreline of the DD in this stent region was alternatively traced within a 0.74 mm mean error. The automatic segmentation of endovascular devices during EVAR is feasible and accurate; it could be useful to perform elastic registration of the vascular lumen during endovascular repair.

1. Introduction

Surgical repair of the aneurysmal segment remains the gold-standard treatment of abdominal aortic aneurysm (AAA). However, postoperative mortality rises from 4.6% [1] to approximately 10% [2] when the patient suffers from severe comorbidity. The alternative is an interventional procedure consisting of endovascular repair (EVAR) with stent graft (SG) [3]. Lower perioperative mortality and morbidity rates have been reported for EVAR, even though the durability of aneurysm exclusion is compromised by frequent endoleaks that prolong the intervention or require re-intervention. The endovascular intervention is guided by digital subtraction angiography (DSA) and fluoroscopy in order to properly deliver the SG and seal of the aneurysm while avoiding coverage of side branches such as renal or internal iliac arteries. This meticulous delivery requires skill to position the C-arm to account for parallax compensation. Since vessels are not visible under fluoroscopy, vascular opacification with iodinated contrast agent is required. Contrast-induced nephropathy is, however, a concern in this population with a high prevalence of renal failure [4]. Moreover, the recently introduced fenestrated SG [5] requires precise vascular mapping to position and align the fenestrations of the SG with targeted vascular branches (renal or digestive arteries) of the aorta.

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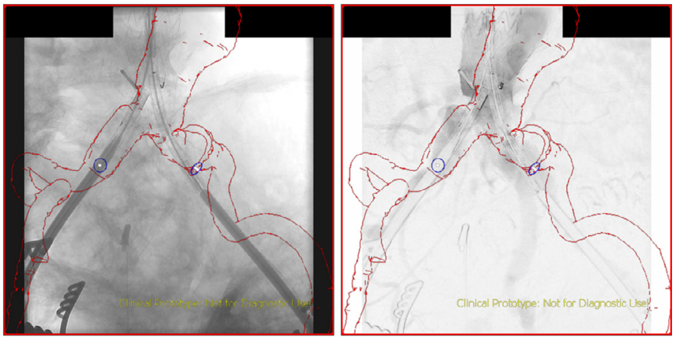

(a) Fluoroscopy (b) DSA

Fig. 1. Vascular deformation observed during endovascular repair. The lumen on the pre-operative CT is outlined in red and the ostium are tagged in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.1. Related work

Improving the fluoroscopic guidance during the EVAR procedure is the subject of intense research effort. Some software solutions are already available such as fusion of the preoperative multidetector contrast CT (MDCT) used for intervention planning with live fluoroscopy. The vascular structure extracted from the MDCT can be segmented [6–9] or simply accentuated[10]. This volumetric information is then registered on live fluoroscopic images, either directly on the 2D image (2D-3D registration) [8,10,11] or with a perioperative cone-beam CT acquisition (3D-3D registration) [7]. Misregistrations have been observed during these guided interventions interventions [6,7,11–14]. They are caused mainly by patient motion and postural changes, as well as by the rigidity of endovascular devices inducing deformation of vascular structures. As seen in Fig. 1, the aorta path is shifted and the iliac arteries are heavily deformed. These distortions constitute a major flaw and as a consequence, physicians are reluctant to rely solely on a numerical vascular overlay. In order to overcome the positional drift associated with patient motion, tracking of anatomical landmarks such as the bones can be used. However, the vascular deformation induced by stiff endovascular devices can only be corrected by shape reforming. Using finite element analysis, Kaladji et al. [8] proposed a mechanical model of the vascular structure by submitting the structure to a stiff guidewire in order to estimate the deformation prior to the intervention. This new model was then compared to the live fluoroscopic image at the proper sequence with the guidewire in place. Once registered, the centreline mean error was 2.3 mm. The major drawback of this approach is having a priori knowledge of the type and number of devices to be used and their exact positions. In practise, the interventional radiologist can use different guidewires and catheters at different locations, depending on the progression of the catheterization/intervention process making prior calculation of the different procedural steps very cumbersome.

Segmentation strategies of endovascular devices have been studied for many years beginning with the segmentation of guidewires [15–24] and catheters [25–29], followed by deployed stents [30–32]. More recent works show promising performance that relies on anisotropic filtering combined with active contour segmentation or probabilistic line segment reconstruction. Radiopaque markers are frequently inserted in catheters to improve their detection under fluoroscopy. Detection of these radiopaque markers has frequently been used for oncology radiation targeting [33–38]. Classical pattern matching techniques are the most popular segmentation approaches proposed along with intensity correlation matching: a method that relies entirely on distinctive metrics [39]. Since fiducial markers are quite visible and have distinctive features, no marker enhancement filtering technique has yet been reported.

1.2. Contribution

Here, we propose a real-time deformable vascular model that uses the current position of endovascular devices as determined by live fluoroscopic images. This simple model could potentially improve the vascular overlay and reduce the need for contrast agent. The proposed model is deformed by the live position of endovascular devices, therefore an automatic (and real-time) identification and segmentation is mandatory.

This paper presents an algorithm workflow to automatically segment relevant endovascular devices used during AAA EVAR. The two major arterial devices considered are the pigtail catheter (PC) and the stent delivery device (DD). In these arteries, There segmentation is a milestone to enables elastic deformation of vascular structures and to eventually improve the accuracy of 2D/3D registration. There are no reports on endovascular tools that have unique imaging characteristics that have not yet been segmented. In addition, the filtering enhancement of endovascular tools on live fluoroscopy is often neglected as is the case for the radiopaque markers and while of interest, no filtering strategies have been reported.

The materials and methods present, at first, the analysis of enhancement filtering. An original filtering technique is detailed and compared with similar and known strategies. The actual segmentation that follows is tested offline on a large dataset of images taken during EVAR interventions.

2. Materials and methods

Typically, the EVAR procedure starts with the insertion of stiff guidewire that initiates the deformation of the vascular structure. This follows a 5-French PC in the abdominal aorta through the contralateral iliac artery prior to the insertion of the DDs (main and contralateral). This PC enables serial contrast injection to guide SG delivery at different steps of the procedure for digital subtraction angiography. The radiopaque (graduated) markers are evenly spaced and are used for measurement and alignment on live fluoroscopy. Afterwards, the main body DD- a 16- to 22-French sheath, including the folded main body SG component, is advanced over a stiff guidewire through the ipsilateral femoral artery. Finally, after cannulation of the contralateral limb of the main body through the contralateral femoral artery, a contralateral DD (between 12- and 18- French) is advanced over a stiff guidewire to complete the AAA exclusion and to maintain the perfusion of the ipsilateral leg. The stiff guidewire and the DDs are known to deform the vascular structure [12] (Fig. 1). The PC and the DDs are the endovascular devices that must be segmented automatically in order to perform an automatic deformation of the vascular structure.

2.1. Segmentation of the pigtail catheter

The segmentation in image analysis is usually achieved by a 3-step procedure. First, the original image is filtered to enhance the geometrical aspects of the object of interest while blurring the rest of the image. Second, the object of interest is then segmented using various methods based on adaptive thresholds, shape and optimization schemes. Lastly, the data is analysed for concordance to specific features. The method proposed here for the segmentation of the radiopaque marker of the PC follows this classical approach.

2.1.1. Existing filters

Although effective, filtering techniques in radiopaque segmentation have not been reported but the enhancement of blob-like structures has been more documented. Hence, small structures are highly responsive to the second derivative. Our first candidate is the classical Laplacian of Gaussian (LoG), combining the derivative with smoothing [40]. The second candidate, the Hessian matrix, is more